THE SNOWFALL OF THE UNITED STATES

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The Economics of Snow

THE margin of temperature difference between rain and snow is a narrow one. It is, however, one of the most critical points in man's relation to the atmosphere, because of the fundamental differences in the economic effects of rain and snow. Snow, especially the deep snows which lie for weeks and months on the mountains and plateaus of the semi-arid West, furnish a slower and therefore a more lasting natural supply of water for power, for irrigation, and for general use than does rain, which has a quick run-off. In the drier sections of the United States many of the most important problems with which engineers have to deal, whether in connection with railroad construction and operation, or hydraulics, or irrigation, or general water-supply, are connected with the depth and conditions of snowfall, and with the amount of water which its melting will supply. In California, the mountain snowfall has well been termed the life-blood of the state, and the same is true of most of the vast territory west of the Rocky Mountains. The farmers throughout the districts of deficient precipitation are deeply concerned with the amount of winter snowfall, for the melting snows supply most of the water needed for irrigating the crops. A winter snow-cover prevents deep freezing of the ground; protects grasses and fall-sown crops, and provides spring moisture for growing vegetation.

When sufficiently deep, and more or less permanent, snow makes sleighing possible, and greatly facilitates lumbering operations over the forested sections of the northern and northeastern states. Heavy winter snows, on the other hand, interfere with railroad operation, sometimes causing serious and expensive interruption of transportation, and involving great expense for the removal of snow from steam and electric railroads, and from city streets. At the same time, such conditions furnish employment to thousands of men. An open winter, with light snowfall, means a saving of millions of dollars to the railroads and cities in the snow-belt. In the latitudes of heavy snowfall, snow-sheds, snow-fences and snow-ploughs are essen-

tial to a reasonably uninterrupted railroad service. The demand for all kinds of rubber footwear in the states where snowfall is a common winter characteristic has given rise to one of the important manufacturing industries of the snow-belt. The use of snowshoes and of skis, for winter sports as well as for ordinary means of locomotion, is another result of a winter snow-cover.

The Measurement of Snowfall

The accurate measurement of snowfall presents many difficulties, and no reasonably simple, practical and satisfactory method for general use has yet been devised. Most of the available records are still of rather doubtful accuracy. What is needed is careful determination both of the depth of snow as it falls and also of the water-equivalent of the snow when melted. The widely-quoted average ratio of ten inches of snow to one inch of water is subject to very wide fluctuations, for it depends upon the varying density and quality of the snow. The essential difficulty in obtaining accurate measurements by means of any ordinary form of gauge results from the effect of the wind in preventing the snow from falling into the gauge. In calms, or during light winds, there is little or no error, but when there is much wind such a gauge, unless properly protected or screened in order to break the force of the wind, will give too small a catch, the deficiency becoming greater as the wind velocity increases.

In view of the economic importance of the amount of water available for irrigation and power in the western states, considerable study has been made, especially during recent years, of the whole problem of the more exact determination of the depth of snowfall and of its water-equivalent. Various improvements in snow-gauges which weigh the snow directly have been made by Marvin, Fergusson, Rotch and Fitzgerald, but there still remains the difficulty of securing an accurate catch. Professor Charles F. Marvin, the present Chief of the Weather Bureau, has devised a large shielded weighing gauge which has given fairly satisfactory results at some stations, but there have been difficulties with it on account of the blocking of the top of the collector during wet and sticky snows and by frozen snow, as well as by reason of its being crushed by the weight of very deep snow. In snows which accumulate to a depth of many feet a very large gauge becomes necessary, and there are many difficulties which are not met with where snows are light. In the regions of very heavy snowfalls on the higher unin-

habited elevations of the western states there is the difficulty of visiting the gauges during the winter, and of constructing a gauge of some sort which may catch, and record, the snowfall of a whole season. Snow "bins" of various forms, standpipes, platforms, and other devices have been tried, without much success. Various methods have also been used for measuring the depth of snow by means of snow-stakes, and of melting cross-sections of snow in order to determine the average density of the snow cover. Professor J. E. Church, Jr., of the University of Nevada, has obtained good results by using snow-stakes, and by cutting out and measuring tubular sections of the deep snows of the Sierra Nevada by means of his improved "snow sampler."[1]

In this instrument, vertical snow cylinders are cut out by means of several sections of tubing of small diameter, and the water content of this sample is determined by weight, the dial of the spring balance being graduated to indicate the depth of water instead of its weight. In order to ascertain in advance the amount of water which will each year be available from the melting mountain snows, surveys have been made of type watersheds in selected areas of the West, and the amount of snow on adjacent watersheds is then estimated. Surveys of this kind will undoubtedly be greatly extended by the Weather Bureau in the near future.

In the matter of forecasting the amount of water available from snow, the rate of melting of the snow, as well as the amount of evaporation from the snowfields and from the surfaces of water storage basins are obviously of great consequence. Some years ago (1908) Professor J. N. Le Conte devised a method for determining the mean rate of melting of the snows in the Sierra Nevada Mountains of California.[2] In order to obtain the true rate of melting, the average date at which the snow is of a certain depth is determined. The mean curve of melting is then compared with the actual curve of a given year. When the actual curve falls below the mean as a whole the season is dry, the rains are likely to be low, and travel in the mountains will probably be easy as early as July. When, on the contrary, the actual curve of melting is slower than the

[1] J. E. Church, Jr., "Snow Surveying: its Problems and their Present Phases with Reference to Mount Rose, Nevada, and Vicinity," *Proc. 2d Pan-Amer. Sci. Congr.*, Sec. II., Vol. II., 8vo, Washington, D. C., 1917, pp. 496–547 (a general discussion of the problem, with references to the literature).

[2] J. N. Le Conte, "Snowfall in the Sierra Nevada," *Bull. Sierra Club*, June, 1908.

mean, it may be inferred that the snows will last longer, and that high water will come later. This matter has been discussed by Professor A. G. McAdie, who has designed a model by means of which the actual curve of melting for a given season may be compared with the mean curve, and thus the probable date of the disappearance of the snow may be determined.[3]

Professor A. J. Henry, of the Weather Bureau, has investigated the weather conditions which may modify or control the disappearance of the snows in the High Sierras of California.[4] The most pronounced "snow flood" in the United States is that which passes annually down the Columbia River and which is due almost wholly to the melting snows on the mountains of the Columbia drainage basin. Otherwise "snow floods" are generally rare in the United States, flood conditions being usually brought about by a combination of snow-melting and of heavy rainfall. In the high Sierras, the most favorable weather conditions for the conservation of the snow-cover are low temperatures and little wind movement. When these conditions prevail, the average loss by evaporation is about three quarters of an inch per day. Relatively high temperature, active wind movement, and abundance of strong sunshine are the most favorable conditions for the conservation of a snow cover. Under these conditions, the loss of freshly fallen snow may average ten inches a day, and of old snow, three to four inches. In connection with the disappearance of snow, the influence of forests upon the rate of melting deserves more extended study than it has yet received. To cite but one illustration, it appears that in the case of the yellow pine forest near Flagstaff, Ariz., the spring rate of melting in the forest is noticeably slower than that over the adjacent grass and farm-land park area.[5] The observations of snowfall at the regular stations of the Weather Bureau are made by means of ordinary gauges, the amount of melted snow being included in the general record of "rainfall." In addition, the number of inches and tenths of inches of snowfall for each 24-hour interval is determined as

[3] A. G. McAdie, "Snowfall at Summit, Cal.," *Mo. Wea. Rev.*, Vol. 38, 1910, pp. 940–941; "Forecasting the Supply of Water for the Summer from the Depth of Snow," *ibid.*, Vol. 39, 1911, pp. 445–447; "Forecasting the Water Supply of California," *ibid.*, Vol. 41, 1913, pp. 1092–1093; "The Principles of Aerography," 8vo, Chicago and New York, 1917, pp. 226–229. See also J. N. Le Conte, *loc. cit.*

[4] Alfred J. Henry, "The Disappearance of Snow in the High Sierras of California," *Mo. Wea. Rev.*, Vol. 44, 1916, pp. 150–153.

[5] A. J. Jaenicke and M. H. Foerster, "The Influence of a Western Yellow Pine Forest on the Accumulation and Melting of Snow," *Mo. Wea. Rev.*, Vol. 43, 1915, pp. 115–124.

accurately as possible by measurements made at places where the snow is of average depth.[6]

These observations have been used as the basis of the snowfall maps of the United States hitherto published.[7]

The Mean Annual Snowfall Map of the United States

The standard snowfall map of the United States at the present time was constructed by Dr. Charles F. Brooks and originally published in England.[8]

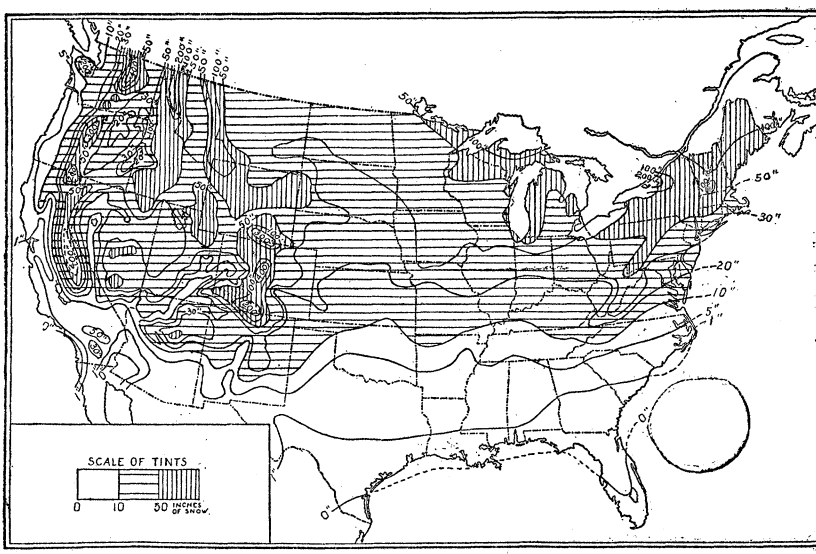
It is here reproduced, with some slight modification, for the first time. The map is based upon the snowfall observations from July, 1895, to June, 1910. In all, the data for over 2,000 stations were used. Of these, 159 had a continuous record for the fifteen years, and these were given the most weight. The data for stations with shorter records were given less and less weight as the length of the period of observation decreased. In previous maps the observations used came mostly from the larger cities, the majority of which are not far from sea-level.

[6] Current data regarding snowfall may be found in the "Annual Reports of the Chief of the Weather Bureau"; in the *Monthly Weather Review* (including the *Annual Summary*), and in the monthly and annual reports of "Climatological Data" which are issued for the section centres, each section as a rule corresponding to a state. Averages, covering periods of years, may be found in the "Summaries of Climatological Data by Sections," and in A. J. Henry: "Climatology of the United States," *Bulletin Q*, U. S. Weather Bureau, 4to, Washington, D. C., 1906. Both of the last-named publications also contain brief statements concerning snowfall in their texts. Maps showing the depth of snowfall for each month appear regularly during the winter in the *Monthly Weather Review*, and the depth of snow on the ground is charted weekly during the season in the *Snow and Ice Bulletin*. All of the above are regular publications of the Weather Bureau.

[7] The first snowfall map of the United States was constructed by Professor Mark W. Harrington on the basis of data covering the general period 1884 to 1891. A reproduction may be found in F. Waldo, "Elementary Meteorology," 8vo, New York, 1896, Fig. 108, p. 344. A later chart, for the general period 1884 to 1895, the data covering varying numbers of years from 3 to 11, by Professor A. J. Henry, was published in the *Monthly Weather Review*, Vol. 26, March, 1898, Ch. XI., Text, p. 108. A note is appended to the chart, stating that the snowfall of the Sierra Nevada and Rocky Mountains is "much greater" than is shown on the chart. Monthly charts, showing the average depth of snowfall from October to May, inclusive, based on records of varying lengths from five to twenty years, mostly not over seven years (1884–1891), were published in 1891 by Professor Harrington (*Bulletin C*, U. S. Weather Bureau, 1894, Pl. XVIII., text, pp. 16–17).

[8] Charles F. Brooks, "The Snowfall of the United States," *Quart. Journ. Roy. Met. Soc.*, Vol. 39, 1913, pp. 81–84, Pl. II.

Hence the snowfalls on the mountains and at the higher elevations generally were not indicated. In the case of the present map, the author has made use of the observations which have been obtained at the higher altitudes as well, and, taking account of the probable effect of the topography, has for the first time shown the actual conditions of snowfall over the whole country with as close an approach to accuracy as is possible with the observations which were used. When more numerous, and later data come to be taken into account, a more detailed and a more accurate map can, of course, be constructed.



MEAN ANNUAL SNOWFALL MAP OF THE UNITED STATES. (C. F. Brooks.)

The lines on the accompanying map show the average annual depth of snowfall, in inches, on the general basis of 15 years of observation. They do not, therefore, indicate the maximum or the minimum depths which have been recorded in this period; nor the depths in any single year; nor does the 0-inch line show the extreme limit to which snow has ever fallen. It must, furthermore, be remembered that the amount of snowfall varies greatly, and very irregularly, from year to year. Years of abundant snows, well exceeding the average depth, alternate irregularly with years of deficient snowfall. This variability depends on the length and the severity of the winter, and on the number and the intensity of the snowstorms.

General Controls of Snowfall; Snowstorm; 24-Hour Snowfalls

The major controls of snowfall in the United States are the temperature; the season of precipitation; the frequency and intensity of winter storms; the topography; proximity to primary sources of moisture-supply, such as the oceans and the Great Lakes, and the exposure to damp winds. The heaviest snowfall is to be expected where the winter season naturally has abundant precipitation, and where the temperatures are low enough to give snow instead of rain. Such conditions are found on certain mountains, as on the Sierra Nevada, for example, where the low temperatures are due to the altitude, or on damp lowlands, as in the vicinity of the lakes, where the climate is continental and therefore the winters are cold. The temperature control over snowfall is clearly indicated in the decrease in the amount of snow towards the south, and also along the Atlantic coast, where, during the winter months, rain frequently falls with onshore winds while it is snowing in the interior, not many miles away.

Over nearly all of the eastern United States the northeast wind, being both cold and damp, is the chief snow-bringer. A "northeast snowstorm" is a familiar winter characteristic, especially along the Atlantic coast.[9] The heaviest snows usually come in February or even in March over the northern sections. The northwest winds, blowing on the rear of the storms, are plenty cold enough to give snow, but are generally too dry. Snow flurries, rather than deep and general snows, are therefore usually associated with them. Exceptions must, however, be made in the case of windward mountain slopes, as in the Appalachian area, and of places to leeward of the Great Lakes, where the northwest winds may bring heavy snowfalls. In an intensive study of two great snowstorms, Dr. Brooks has brought out certain characteristics of snowfall distribution which are doubtless of common occurrence.[10]

Snow fell over a wide area on each side of the storm track. The heaviest snows came with northeast winds, over a belt about 100 to 200 miles in width, to the north of the track. The northwest winds, in the southwest quadrants of the storms, sprinkled light snows over the country as far as about 300 miles to the southward of the track. A distinct "patchiness" in the

[9] Charles F. Brooks, "The Snowfall of the Eastern United States," *Mo. Wea. Rev.*, Vol. 43, 1915, pp. 2–11.

[10] Charles F. Brooks, "The Distribution of Snowfall in Cyclones of the Eastern United States," *Mo. Wea. Rev.*, Vol. 42, 1914, pp. 318–330; Chs. 11.

distribution of these snowfalls resulted from local topographic features.

It is a general characteristic of heavy snowfalls in eastern districts, especially on mountains, that they are accompanied by fairly high winds. A marked contrast to this condition is found in the region of very deep snows on the Sierra Nevada Mountains of California, for example, where the winds are always relatively light.

The greatest 24-hour snowfalls in the different sections of the country have been summarized by Professor Henry as follows: northeast, 2–3 ft.; elsewhere east of the Mississippi River, from 8 inches (Ohio Valley) to 18–20 inches (along the Lower Lakes); southern states, 4–8 inches; Mississippi Valley, 5 inches (Vicksburg) to 20 inches (St. Louis); northern plains, 9–17 inches; Rocky Mountains, 8–24 inches; Plateau and Northern Pacific coast, 10–20 inches.[11]

General Distribution of Snowfall in the United States

Snow falls regularly every winter over by far the greater part of the United States. The only sections which seem to be exempt from even occasional snowfalls are southern Florida and the lowlands of southernmost California adjacent to the ocean. There is considerable variation in the latitudes which mark the southernmost limits of snowfall in any given winter, but for purposes of convenience and of easy memorizing, the limiting latitudes of regular and of occasional snowfall may be broadly generalized as follows:

Latitudes of Regular and of Occasional Snowfall

District	Regular	Occasional
Pacific Coast..	45° (northern Oregon)	34° (Los Angeles)
Interior	30° (northern Gulf)	26° (southeast Texas)
Atlantic Coast..	35° (Hatteras)	29° (northern Gulf)

From a practical point of view it may be said that snow does not occur in sufficient amount to lie unmelted on the ground south of San Francisco on the lowlands of the Pacific Coast, or south of Cape Hatteras on the Atlantic Coast. This statement, however, does not hold for inland districts, or for elevated areas. The southern boundary of a regular winter snow-cover, in ordinary winters, may be put at about lats. 41°–42° in the eastern United States, but occasional winters carry the snow-cover a good deal farther south. It is one of the marked climatic characteristics of the eastern United States that snow not infre-

[11] *Loc. cit.*, footnote 6, pp. 58–59.

quently occurs unusually far south, in districts which have very mild winters.

The most striking general facts on the snowfall map are the effects of the topography in causing very heavy snowfalls on the western flanks of the Sierra Nevada and Cascade Ranges (exceeding 400 inches over considerable areas); the "snow-shadow" effect of this western mountain barrier in causing a decrease in the depths of snowfall over the interior plateau districts as a whole, with larger amounts over the mountains and higher plateaus; the heavy snows of the Rocky Mountain system, averaging considerably less than on the Pacific Coast mountains, but amounting to more than 100 inches over fairly large areas even as far south as northern New Mexico, reaching over 300 inches in southern Wyoming and 400 inches in parts of the Colorado Rockies. East of the Continental Divide the snowfall rapidly decreases again, the lines of equal depth extending in a general east-and-west direction under the control of latitude. The Appalachian mountains and plateaus carry the lines well to the south (50–100 inches from Maine to Maryland), while the warm waters of the Gulf Stream carry them northward along the coast as far as Cape Hatteras. In the vicinity of the Great Lakes, especially on their lee shores, and thence eastward along the Canadian boundary as far as New England, there is a relatively heavy snowfall (more than 100 inches in northern New England and 80 to more than 100 inches on the lee shores of the lakes). Including the higher altitudes, the annual snowfall may be said to average roughly more than 20 inches over northern and less than 20 inches over southern sections. Most of this snow falls from December to March, but at the higher elevations, and in the northern states, it begins as early as October or even September, and falls as late as April or even May. In general, topography is seen to be the most striking control in the west, and latitude in the east.

The Snowfall of the Pacific Slope

The snowfall over the lowlands of the Pacific Slope is of little importance. It is very light, even in the north, and seldom excites interest except when, at long intervals, snow falls in southern districts where it is so uncommon as to be a curiosity, or when, occasionally, a heavier fall than usual in the northern districts causes comment. Snow is rare on the immediate coast south of the northern boundary of California (latitude 42° N.), but it is frequent on the mountains, even in southern California.

When snow does occur on the lower lands of southern California, it seems always to fall with hail, sleet or rain.

Interest is, however, naturally very great in what has for years enjoyed the distinction of being the area of heaviest snowfall in the United States. This area, which is clearly indicated on the snowfall map, is on the western slopes of the high Sierras of California, and has been closely studied along the line of the Southern Pacific Railroad which connects Sacramento, Cal., and Reno, Nev. Recent discussions by Professor A. G. McAdie[12] and Andrew H. Palmer[13] have brought out many interesting facts regarding this remarkable snowfall.

Over an elongated area of considerable extent stretching along the windward (western) upper slopes of the mountains, the average annual snowfall is over 400 inches, *i. e.*, over 30 feet deep. Another area, also with over 400 inches, is found over the Cascade Mountains in northern Washington, but has not yet been intensively studied. The average annual snowfall at Summit, Cal. (7,017 ft.), for 44 years, is 419.6 inches, and the average for 8 years at Tamarack (8,000 ft.) is 521.3 inches. During the winter of 1879–80, 783 inches of snow fell at Summit, and in 1889–90, 776 inches. At Tamarack, in 1910–11, 757 inches fell. The depth on the ground (9-year average) has been determined as follows (T, Tamarack; S, Summit):

INCHES

	Dec. 1	Jan. 1	Feb. 1	Mar. 1	Mar. 15	Mar. 31
T	19	62	165	183	194	192
S	9	44	122	127	140	118

The total precipitation as rain and melted snow is 48.1 inches at Summit and 57.5 inches at Tamarack. These totals by no means represent a very heavy annual precipitation. The significant fact is the proportion of the whole which falls as snow. The Pacific Slope has dry summers and a well-marked winter maximum of precipitation. This maximum results from a combination of various factors, among which the more important are the general winter storms and the prevalence of moisture-laden onshore winds which, in ascending the then cold slopes of the higher mountains, are cooled to temperatures below freezing. This winter maximum is very distinct over the lowlands and valleys, but is less marked at the higher levels. The increase in annual precipitation with increase of altitude, which

[12] See footnote 3.

[13] Andrew H. Palmer, "The Region of Greatest Snowfall in the United States," *Mo. Wea. Rev.*, Vol. 43, 1915, pp. 217–220, with illustrations.

is a general characteristic of mountains, is rapid up to a certain height, after which the rate lessens, and finally there is a decrease in precipitation with altitude. A maximum amount of rainfall, including melted snow, is reached at between 6,000 and 7,000 feet.

Railroad operation in this region shows many responses to the heavy snowfall, as all travellers over the Southern Pacific route, through Summit, well know. The famous "thirty miles of snowsheds" cost $42,000 a mile over single track and $65,000 over double track. About $150,000 is spent annually for upkeep and renewals. The life of a shed averages a little over twenty years. Fire-fighting trains are kept always in readiness in case the sheds take fire, which they often do. The weight of the snow is so great that sections of the sheds occasionally collapse. A heavy rain and snow gauge has been completely crushed by the snow, and a fence made of two-inch boiler flues has been bent. The gables of the houses are all built at sharp angles, so that the snow may slide off. Some very recent observations on Mt. Rainier, Wash., indicate that the snowfall in that district is extraordinarily heavy.[14] Daily records of snowfall were kept during most of the season of 1916–17 at Paradise Inn, on the south slope of Mt. Rainier, at an elevation of 5,500 feet. Observations were not begun until November 24, 1916, but from that date until the last snowstorm before midsummer, 1917, the total depth of snowfall was 789.5 inches. The record at Paradise Inn is the first which has been obtained west of the summit of the Cascades in Washington at so great an elevation. The railroads cross the mountains at comparatively low levels. The season of 1916–17 does not appear to have been one of unusually heavy snowfall, nor is Paradise Inn located at what would theoretically seem to be the region most favorable for a maximum precipitation. It is not unlikely, therefore, that still deeper snows will eventually be recorded at greater altitudes than 5,500 feet on Rainier, which may some day deprive the Sierra Nevada of California of the distinction of having the greatest snowfall in the United States.

The importance of the water-supply from the melting snows of the higher mountains on the Pacific Slope cannot be overestimated. Millions of dollars' worth of water, for irrigation, for power, and for general city and domestic use, are obtained each year from these snows. Without them, most of the valleys and lowlands on the coast would be unable to support their

[14] Lawrence Foster, "Snowfall on Mt. Rainier," *Mo. Wea. Rev.*, Vol. 46, 1918, pp. 327–330.

present crops, and the population of the region would never have attained its present numbers.

SNOWFALL OVER THE WESTERN PLATEAU REGION

Over the western plateau area, between the Sierra Nevada-Cascade ranges on the west and the Continental Divide of the Rocky Mountains on the east, most of the winter precipitation comes in the form of snow. The essential features of the snowfall distribution are the general decrease over the valleys and less elevated portions from 20 to 30 inches in the north to less than 5 inches and even to 0 inches in the south. Over these districts of light snowfall the ground usually does not remain covered many days at a time, and in the region of the lower Colorado River, in southwestern Arizona and southeastern California, snow is rarely seen except on the mountains. The mountains and more elevated plateaus have decidedly heavier snows. A maximum of over 400 inches is reached in some parts of Colorado; of 300 inches in southern Wyoming, and of over 100 inches in many places from Idaho and Montana on the north to northern New Mexico on the south. The snowfall in the Colorado mountains is much greater than the summer rainfall, and comes largely in the spring months. Most of the rivers of the plateau states have their sources in the higher mountains, and the slow melting of the snows, which usually last well into the summer, supplies these streams with water which is essential for irrigation. The maximum stream-flow ordinarily comes in late spring or early summer, when the melting of the mountain snows is most rapid. It is a saying among the Indians of Arizona that when the last snow disappears from the mountain tops, the late summer rains are about to begin.

SNOWFALL ON THE GREAT PLAINS

Lying to leeward of the Rocky Mountains, and being far from any considerable source of water vapor, the plains inevitably have relatively little snowfall. Their total annual precipitation is less than 20 inches, and most of this falls in summer. Thus winter is a dry season, and the snowfall which it brings is light. Even in the extreme north, where the winters are very cold and practically all the precipitation of the five or six colder months is in the form of snow, the average annual snowfall is under 50 inches. The winter storms do not, as a rule, give much snow. Even the "blizzards" are not usually accompanied by heavy snows. They are dangerous to cattle, and occasionally

to human beings, because of the bitter cold of their northerly winds, and because these same winds carry fine ice spicules and are also filled with blowing snow which makes it difficult or impossible to see. Severe blizzards are, as a matter of fact, not as common as most people think. A whole winter sometimes passes without a typical blizzard.

Over the southern plains, owing to the warmer winters, the snowfall decreases to less than 10 inches, and even to less than 5 inches in western Texas and southern New Mexico. The number of days with snowfall also decreases, from an average of 40 or 50 in the north to 5 or 10 in Oklahoma, and to less than 5 in extreme southwestern Texas.

It is a characteristic of the snowfall over the northern plains that most of it falls at temperatures well below freezing. For this reason it is light and dry, and is easily carried by the strong winds, which blow it into ravines and other depressions, leaving the ranges for the most part bare and accessible for grazing. In the south, the snow soon melts under the warm sun.

Over the mountains which border or interrupt the plains, it snows more frequently and during a longer season. The melting of these deeper snows furnishes much of the water which is used for irrigation along the rivers flowing to the eastward towards the Mississippi.

Snowfall of the Eastern United States

In the eastern half of the country, the dominant control over snowfall is latitude, as is evidenced by the general east and west trend of the lines of equal depth of snow on the map. Subordinate, but nevertheless important controls are found in the effects of topography (Appalachians, Adirondacks, White Mts. of New Hampshire); of the frequency of cold, damp storm winds (Great Lakes and northeastern sections), and of the warm waters of the Gulf Stream (southern Atlantic coast). The depth of snow decreases to the west of the lakes because winter is there a relatively dry season, and to the south because of the higher temperatures. A detailed study of the snowfall of the eastern United States has been made by Dr. Charles F. Brooks.[15] This shows clearly the local modifications which re-

[15] Charles F. Brooks, "The Snowfall of the Eastern United States," *Mo. Wea. Rev.*, Vol. 43, 1915, pp. 2–11. Includes original charts showing the average depths of snowfall by months, from September to May; the average annual snowfall (1895–1913); the average annual number of days with snowfall; the mean annual, maximum and minimum annual, and extreme annual range of snowfall about the Great Lakes, for the period 1895–1910; also monthly charts showing the directions of the snow-bearing winds.

sult from the topography and from exposure to damp winds. More snow is seen to fall on the western than on the eastern slopes of the Appalachians, except in Vermont.

Over the northern tier of states in the eastern half of the country snow is a factor of considerable economic importance, especially over northeastern sections where the depths are greatest. Sleighing is often possible for weeks at a time in winters of abundant snowfall, the depth of snow on the ground reaching two or three feet in certain sections. Such snows greatly facilitate the lumbering industry by making it possible to use heavy sledges for hauling the logs out of the forests. "Open winters," on the other hand, make lumbering difficult and expensive. Warm winter rains are especially characteristic of the Atlantic coast sections and naturally occur with increasing frequency toward the south, quickly melting any snow which happens to be lying on the ground. In the spring months, heavy rains of this type, or unseasonably high temperatures unaccompanied by rains, not infrequently cause a very rapid melting of the deeper snows lying in the mountains, and produce freshets and floods in the Ohio and other river systems of the northeast.

The season of snowfall over northern sections is a long one. Snow in measurable amounts may fall as early as October, or even in September in the White Mountains of New Hampshire and in the Adirondacks, and as late as May. Indeed, snowstorms of considerable intensity have occurred in April, but the heaviest snowfalls usually come in February, or at times early in March. The general snow-cover advances as a whole from north to south with the advance of winter, very irregularly and often with many retrogressions as well, its southern margin being uneven and broken under the control of varying conditions of topography, storm control and temperature. It usually reaches its southermost limits in January or in February, and then retreats northward again. This seasonal advance and retreat, with its many irregularities, can be studied to advantage on the *Ice and Snow Bulletins* of the Weather Bureau.

Towards the south, as latitudes of milder winters are reached, the season during which snow may fall becomes shorter and shorter. Less and less of the precipitation of the colder months falls as snow, and more and more comes in the form of snow and rain mixed, and then of rain. The number of days with snowfall decreases. Thus, while days with snowfall average over fifty a year over most of the Lake region and St. Lawrence Valley, including northern New England, there is an

average of only one day with snowfall along a line reaching from southeastern North Carolina to south of Vicksburg, Miss. (fifteen years). The mountainous section of all the southern states which are crossed by the Appalachians have more days with snowfall, and more snow than the surrounding lowlands and valleys. There are, for example, fifty days with snowfall a year as far south as Elkins, W. Va., but the accumulation of snow is not sufficiently great to be a factor in causing dangerous spring floods as is the case farther north. With decreasing latitude, snow lies on the ground less and less of the time, and soon becomes an almost, and then an entirely, negligible factor. When it falls over much of the South, it is merely a matter of temporary discomfort, melting soon. Southern South Carolina is practically exempt from snowfall. In Georgia, snow, when it falls, melts almost immediately, although it may remain on the ground a few days in sheltered places in northern sections of the state. It is not an uncommon occurrence for a season to pass without snow enough to cover the ground over the northern portions of the northern gulf coast states. Farther inland, as, *e. g.*, in Tennessee, the ground is rarely covered more than a very few days at a time, but unusually heavy snowstorms, at long intervals, may result in a snow-cover which lasts a week, or even more.

Over the sections immediately adjacent to the Gulf of Mexico, snow becomes practically negligible. Occasionally, at long intervals, there are measurable amounts in northern and even central Florida. The gulf sections of Alabama, Mississippi and Louisiana have a 15-year average of less than one inch, and an average of less than 1 day with snowfall annually. Years may go by without any snow along the Texas coast and in the lower Rio Grande Valley. Much interest attaches to the occasional occurrence of unusual snowfalls in the south. During spells of exceptional cold, snow may fall to the depth of a good many inches at various localities along the southern Atlantic and Gulf coasts, and with diminishing depth even as far as extreme southeastern Texas. On such occasions, thousands of people witness their first snowstorm.

Sleet and Ice Storms

Sleet and ice storms are so closely associated with snowstorms in the eastern United States that it is often difficult to forecast snow because a storm of sleet or ice may occur instead. According to the present Weather Bureau definition, sleet is precipitation that occurs in the form of frozen or partly frozen

rain. It is formed by rain falling through a relatively warm stratum into or through another stratum which is cold enough to freeze some or all of the rain drops. When, under these general conditions, rain drops fall to the earth's surface and freeze on coming in contact with solid objects on that surface, an ice-storm results. Telegraph, telephone and trolley wires, trees, sidewalks and streets are then covered with an icy coating. Service is thus often interrupted because of broken wires, and transportation becomes difficult or dangerous by reason of slippery rails and streets. Considerable damage is often done to forest and fruit trees by such ice-storms. Mr. Verne Rhoades, of the U. S. Forest Service, has called attention to the widespread damage caused by a single ice-storm in the southern Appalachians,[16] and Mr. W. W. Ashe, Forest Inspector of the Forest Service, has pointed out that the damage done by these storms is such that the dates of past ice-storms may be determined by an examination of the trees. In the case of trees damaged by a recent ice-storm along the Blue Ridge Mts., in Amherst Co., Va., evidence was found of injury by two previous storms, about 14 and 35 years, respectively, before the last one.[17] Professor H. C. Frankenfield, of the Weather Bureau, has recently made a study of sleet and ice storms in the United States.[18]

The region of maximum frequency is over a broad central belt reaching from west of the Mississippi eastward and northeastward to the Atlantic. This is, in general, the portion of the country which is crossed by the principal storm areas, with their cold northerly winds to the north and warm southerly winds on the south of their centers. These conditions are essential to sleet formation. Severe sleet storms may occur from November to March, inclusive, and occasionally in April and October to the north of the 42d parallel. It appears that steep northward temperature gradients, and high temperatures over the Gulf and South Atlantic States are necessary for sleet formation, and are usually absent before and during heavy snows. Surface temperatures preceding sleet and ice storms are below freezing, usually between 22° and 28°, and the high

[16] Verne Rhoades, "Ice Storms in the Southern Appalachians," *Mo. Wea. Rev.*, Vol. 46, 1918, pp. 373–374.

[18] H. C. Frankenfield, "Sleet and Ice Storms in the United States," *Proc. 2d Pan. Amer. Sci. Congr.*, Vol. 2, Section 2; Astronomy, Meteorology, and Seismology, pp. 249–257 (discussion, pp. 252–257). Washington, D. C., 1917. (Gives a map showing the average annual frequency of sleet and ice storms, and typical weather maps favorable for their occurrence.)

[17] *Ibid.*

temperatures in the south which precede the sleet are accompanied by southeasterly to southerly winds.

The ice-storms of New England have been discussed in some detail by Brooks,[19] who has based his study chiefly on the very complete records obtained at Blue Hill Observatory, Mass., and has included a consideration of upper-air conditions. Three general types of wind conditions produce ice-storms. These are (1) warm air arriving over residual cold air ("southerly" type); (2) cold air coming in below and warm air arriving above ("northeasterly" type); (3) cold air pushing in from the north or west below a rain cloud ("northwesterly" type). Classifying ice-storms according to the positions and movements of the low and high pressure conditions (cyclones and anticyclones) which produced them, there are seen to be two large groups. The first includes storms with anticyclones in the north dominating southern cyclones, and the second includes those in which the cyclones and anticyclones were in regular sequence.

Is Snowfall Decreasing?

There is a widespread popular belief in many parts of the country, especially in the earlier settled sections of the northeast, that less snow falls now than was the case years ago. In New England, for example, it is customary to speak of the "old-fashioned New England winters" which brought many heavy snowstorms; when snow lay on the ground uninterruptedly all winter, and when sleighing was possible for three or four months without a break. In a question of this kind it is, of course, impossible, to put any confidence in general impressions or in tradition. It is a mistake to place absolute trust in our memories, and attempt to judge such subtle things as differences in snowfall on the basis of such memories, which are at best short, defective, and in the highest degree untrustworthy. The tendency inevitably is to exaggerate past events; to remember a few exceptional seasons which, for one reason or another, made a deep impression on us, and very much to overrate some special event. Individual severe winters which, as they occur, are some years apart, seem, when looked back upon from a distance of several years later, to have been close together. It is much as in the case of the telegraph poles along a railroad track. When we are near the individual poles, they seem fairly far

[19] Charles F. Brooks, "The Ice Storms of New England," *Annals Astron. Obsy. Harv. Coll.*, Vol. 73, Pt. 1, 4to, Cambridge, Mass., 1914, pp. 8, pls. 2 (Abstract in *Mo. Wea. Rev.*, Vol. 42, 1914, pp. 455–457); "Three Ice Storms," *Science*, Aug. 8, 1913, pp. 193–194.

apart, but when we look down the track, the poles seem to stand close together. The difference in the impressions upon youthful and adult minds may account for part of this popular belief in changes of climate. To a youthful mind a heavy snowstorm is a memorable thing. It makes a deep impression, which lasts long and which, in later years, when snowstorms are just as heavy, seems to dwarf the recent storms in comparison with the older.

Changes of residence may account for some of the prevailing ideas about changes of climate. One who was brought up as a child in the country, where snow drifts deep and where roads are not quickly broken out, and who later removes to a city, where the temperatures are slightly higher, where the houses are warmer, and where the snow is quickly removed from the streets, naturally thinks that the winters are milder or less snowy than when he was a child.

The only reliable evidence is that which rests upon instrumental records. Accurate instruments, properly exposed and carefully read, do not lie; do not forget; are not prejudiced. When such instrumental records, scattered though they are, and difficult as it is to draw general conclusions from them, are carefully examined, from the time when they were first kept in this country, which in a few cases goes back a century or more, there is found no evidence of any progressive change in the amount of snowfall. Some winters now bring deeper snows and greater cold, while others are mild and "open." These variations result from differences in the numbers, intensity and paths of winter storms, as is clearly seen by a study of the daily weather maps. This same sort of variability was characteristic of the past, and will continue forever. In other words, a mild winter with light snowfall is just as "old-fashioned" as one with severe cold and heavy snowfall. There were plenty of both kinds of winters in the past. There will be plenty of both kinds in the future.

In his "Climatology of the United States," which was a standard publication in its day (1857), Lorin Blodget, in a chapter on the "Permanence of the Principal Conditions of Climate," speaking of the evidence for and against climatic change, held that "real history would be more valuable than anything else if it could be relied on, but there is great looseness with much exaggeration in everything dating back beyond the use of instruments." Blodget believed that "the Northmen found the New England coast 860 years ago quite precisely the

same in climate as now—wild vines growing in a very few of the most favored spots, and only in these."

Dr. Hugh Williamson is quoted as saying, in 1770, that the winters of the last half-century had been milder than formerly, and Professor Samuel Williams, of Harvard College, whose lectures were among the foundation-stones of American meteorology, asserted that "the winter is less severe, cold weather does not come on so soon." These views sound singularly like those which are heard expressed nowadays. It so happens that the early settlers of New England made a special point of keeping a chronicle of weather conditions, so that we have a record of the character of the seasons running back over three centuries. When these old accounts are examined, it at once becomes apparent that New England had precisely the same variability in its winters in the earlier days of its settlement as now. There are accounts of great cold; of deep snows; of violent winter storms. There are also many descriptions of very mild and open winters. Thus, we read of December and January resembling May and June; of flowers growing in the woods in midwinter; of so little snowfall "as scarcely to give opportunity for enjoying the music of the sleigh-bells"; of "green Christmases"; of "winter turned into summer"; of the "ground bare for the most part"; of little ice; of crocuses up, of wild violets in bloom, and of lilacs "throwing out their leaves" in January.

It has been well pointed out that if a list were compiled of heavy snowstorms, of droughts, of floods, of severe cold, of mild winters, of heavy rains, and of other similar meteorological phenomena, for one of the early-settled portions of the United States, beginning with the date of the first white settlements and extending down to the present day, we should have the following situation. Dividing this list into halves, each division containing the same number of years, it would be found, speaking in general terms, that for every mild winter in the first half there would be a mild winter in the second; for every long-continued drought in the first division there would be a similar drought in the second; for every "old-fashioned" winter in the first group there would be an "old-fashioned" winter in the second. And so on, through the list. In other words, weather and climate have not changed from the time of the landing of the Pilgrims down to the present day.